Effects of External Magnetic Field on PAC Spectrum of Ni.

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Introduction

Effects of external magnetic field on PAC spectrum have been worked out theoretically and summarized in Ref.[1]. When the numerical coefficients are evaluated for the PAC spectrum, $R(t)=[N(\pi)-N(\pi/2)]/[(N(\pi)+N(\pi/2)]$ where $N(\pi)$ and $N(\pi/2)$ are the counts for the stop detectors placed at π and $\pi/2$ relative to the start detector respectively, R(t) reads as eq.(1) for the magnetic field applied vertical to the detector plane.

$$R(t)= b_2 \cos(2\omega_L t) \qquad (1)$$

where ω_L is Larmor frequency and given as $-g\mu_N B/\hbar$, where g is the nuclear g factor. μ_N is the nuclear magneton and B is the hyperfine field at the nucleus. The b_2 is calculated to be -0.132 for the case of ^{111}In (^{111}Cd)[2]. This expression agrees with the classical picture of the nuclear precession with the angular frequency of ω_L, which is detected by the γ ray emission that has the π symmetry and hence should give two maxima during one period of the precession.

For the case of the random spin direction, namely, without any external magnetic field, eq.(2) is obtained for R(t) based on the calculation by Matthias et al.[3].

$$R(t)=b_2 [\ 0.2 +0.4 \cos(\omega_L t)+0.4\cos(2\omega_L t)\ ] \qquad (2)$$

This expression is different from eq.(1) with the presence of the unperturbed term of 0.2 and the 2nd term with ω_L of which amplitude is the same with the third term of $2\omega_L$. The eq.(2) can be derived from the fundamental formulation for PAC[1]. There, the property of 3j symbol, that gives the transition probability among 2I+1 magnetic sublevels, is used to show only the terms $N=(m_a-m_b)=0, \pm1, \pm2$ survive to give the finite amplitude of $N\omega_L$ frequency. Since this probability is independent of the value of I, we have only one precession frequency with $H\neq0$ and only two with H=0 for any I. This is different from the quadrupole interaction where the number of frequency increases with I. (For instance 3 for I=5/2, 6 for I=7/2). So the magnetic interaction gives a much simpler spectrum than that of the quadrupole interaction and will be quite useful for the PAD experiment where a high spin nuclear probe is utilized.

The purpose of the present work is to verify eq.(1) and (2) for ^{111}In in Ni by measuring PAC spectrum with and without the vertical external magnetic field. Although Matthias et al have experimentally shown that eq.(2) is valid for ^{111}In in Ni, they gave the spectrum without extracting the precession term and also no comparison was made for the case with the vertical magnetic field.

The other purpose of the present work is to find an optimum conditions to prepare a Ni specimen with ^{111}In by a diffusion method. For this purpose, the diffusion treatment was performed at lower temperature than the reported ones[4,5] and subsequently the specimen was annealed at higher temperatures stepwisely to find the temperature to give the maximum amplitude in the PAC spectrum.

Experimental

A high purity polycrystalline Ni (99.995% by Johnson-Matthey Inc.,) specimen ($10\times5\times0.2mm^3$) was annealed in 1 atm hydrogen atmosphere for 12 hrs at 400C with 400 μCi of dried $^{111}InCl_3$ solution to diffuse ^{111}In into the Ni bulk. After measuring the PAC spectrum by a three detector system, the specimen was annealed in an UHV for 1.5hrs from 500C to 980C stepwisely. After the each annealing, the PAC spectrum was measured at RT with and without the vertical magnetic field of 0.25T supplied by a pair of permanent magnet. The spectrum was analyzed by a FFT program to obtain the power spectrum.

Results

Figure 1 shows the PAC time spectrum for Ni with the annealing temperature as a parameter. The spectrum with and without the external magnetic field was measured for the temperatures between 873K and 1250K. Figure 2 shows part of the corresponding Fourier spectra for Figure 1. Figure 3 shows the amplitudes of the two components in Figure 2 as a function of the annealing temperature.

Discussion

EFFECTS OF THE EXTERNAL MAGNETIC FIELD

From Figure 1 nd Figure 2 it is evident that two angular frequencies take place for the case without magnetic field and only one for the case with the magnetic field. This result agrees exactly with the theoretical prediction of eq.(1) and (2).

The close inspection of Figure 2, however, reveals that the value of $2\omega_L$ for the $H\neq0$ case is about 4% lower than that of the H=0 case.. This is due to the fact that the hyperfine field at the nucleus is reduced by the external magnetic field. Namely, the external magnetic field H is subtractive from the hyperfine field B or similarly the sign of B is negative. From the measured ω_L for the H=0 case, the hyperfine field B can be determined as-6.34T with knowing the nuclear g factor of ^{111}In (^{111}Cd)[6]. Indeed the ratio of the external field to the hyperfine field, 0.25/6.34=4%, roughly agrees with the observed shift of 4% in the $2\omega_L$. If one can measure the shift as a function of the magnitude of the external field H, one can determine both g and B at the same time with an appropriate extrapolation method for H=0.

AMPLITUDE OF THE PRECESSION PATTERN

As seen from Figure 1 or Figure 3, the amplitude of the precession is quite low right after the diffusion treatment at 400C. It grows with the annealing temperature and reaches to a maximum at 600-700C and then gradually decays between 700 and 1000C.

The low amplitude at 400C can be interpreted that only part of ^{111}In diffuse into Ni bulk as the substitutional impurity and the other part are still on the surface. Indeed Figure 3 as well as Figure 1 reveal that there exists a very low frequency component (10Mrads-1) at 400C or 500C. The site corresponding to this low frequency is not known at present. Possibilities are:(1) ^{111}In adsorbed at the surface or (2) ^{111}In in the $InCl_3$ solution that has not been reduced by the H_2 annealing.

The maximum amplitude R for the $H\neq0$ case is 0.11 at 700C that is comparable with the theoretical value of $|b_2| = 0.132$. So most of ^{111}In are at the Ni substitutional site at this temperature. The remaining part of 0.132-0.11=0.022 should be in the other sites that do not give unique precession frequencies, of which species are not known at present. Indeed Figure 3 shows the magnitude of the a broad frequency distribution above and below $2\omega_L$ increases with the annealing temperature.

Practically, the above results suggest that 700C is the most appropriate temperature if one wishes to prepare a Ni source specimen by a diffusion method.

The present results show the theoretical prediction of eq.(1) and (2) are quite valid with respect to the effect of the external magnetic field (the vertical magnetization) for the case of Ni.

Acknowledgement

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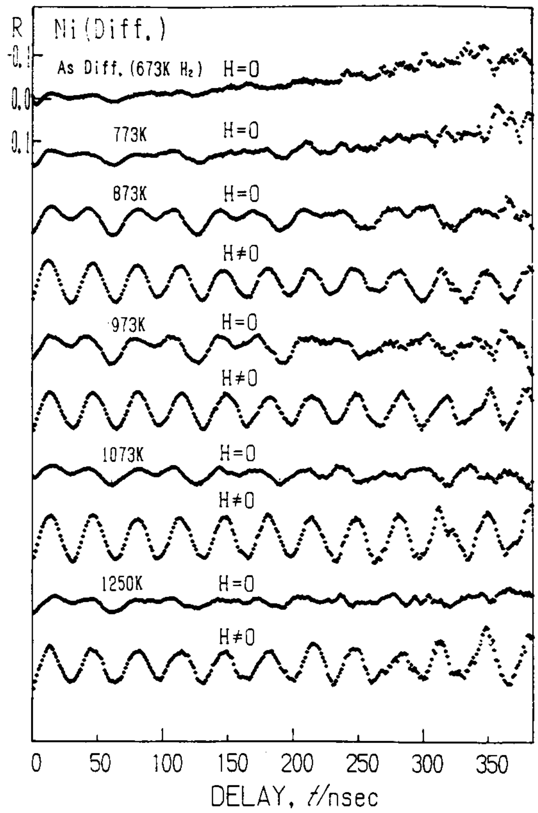

Fig. 1. PAC spectrum by ^{111}In in Ni. The spectra with and without the external magnetic field are shown. RT measurement.

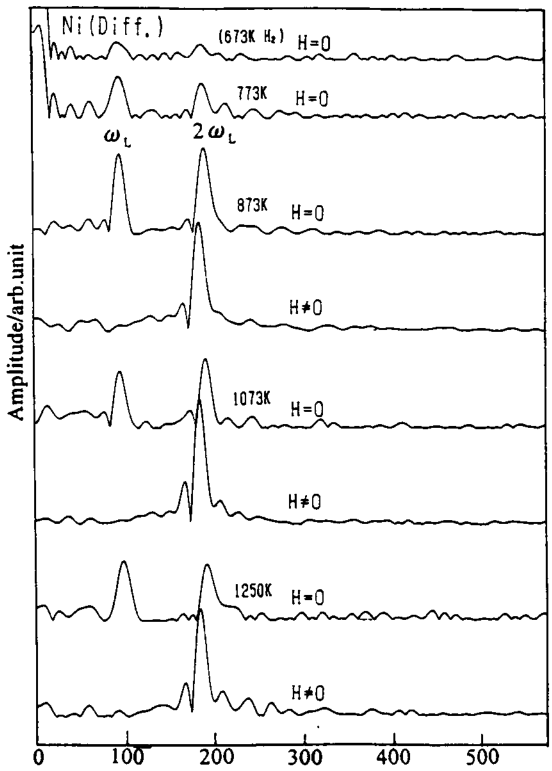

Fig. 2. A Fourier power spectra for Fig. 1. Two frequencies without the external magnetic field and only one with the field.

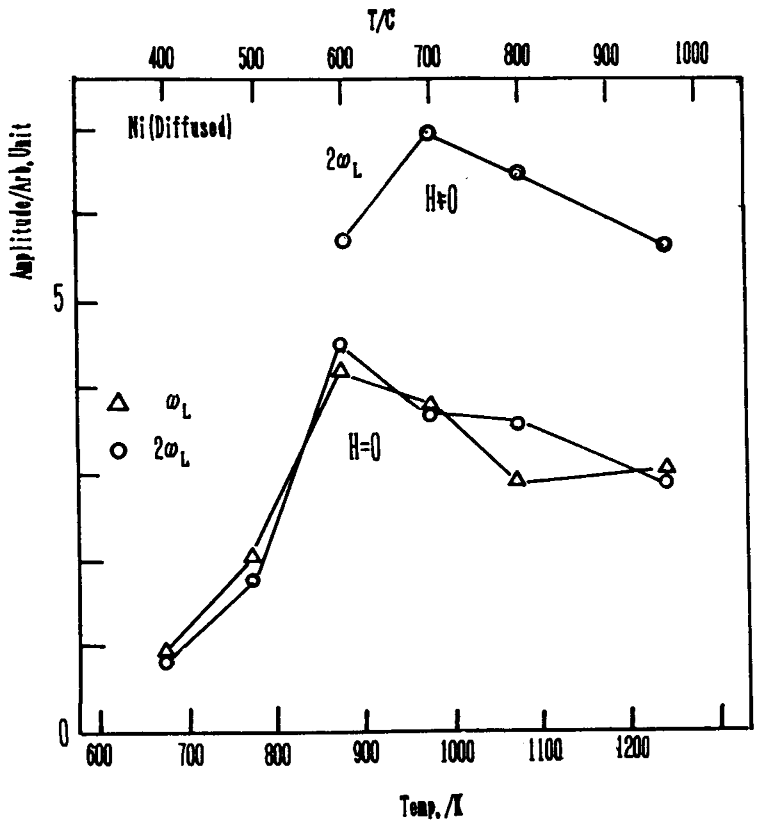

Fig. 3. Amplitudes of the two components as a function of the annealing temperatures after the diffusion treatment at 400C.